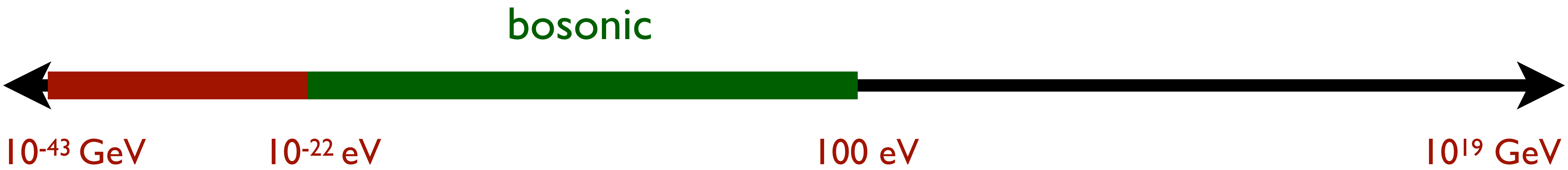
Experimental Signals of Ultra-light Dark Matter

Surjeet Rajendran,
UC Berkeley

The Dark Matter Landscape

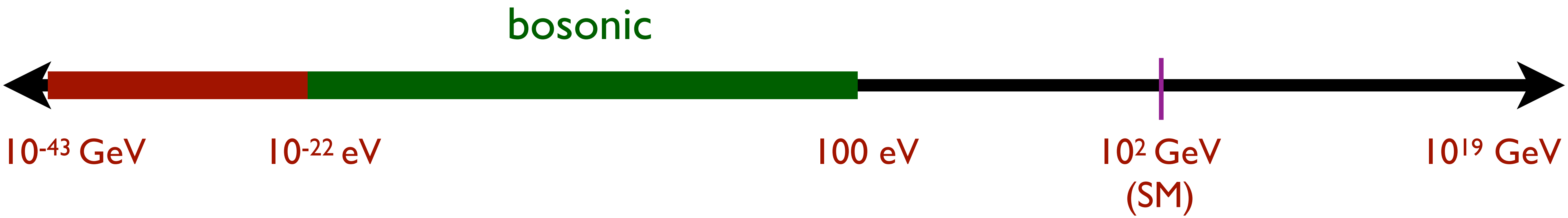
10^{-43} GeV $\longleftrightarrow$ 10^{19} GeV

The Dark Matter Landscape



Fit in galaxy

The Dark Matter Landscape



Fit in galaxy

Standard Model scale ~ 100 GeV

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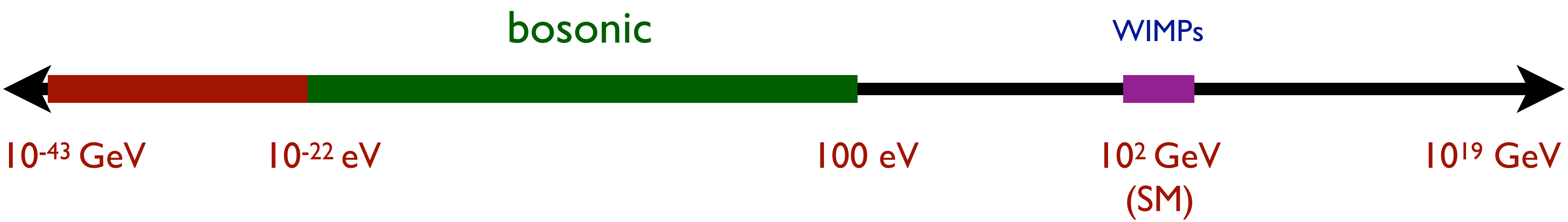

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One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

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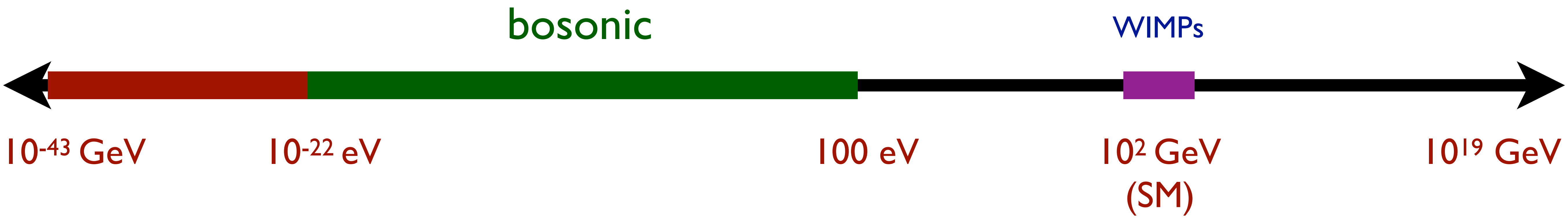

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Other Generic Candidates: Axions, Massive Vector Bosons

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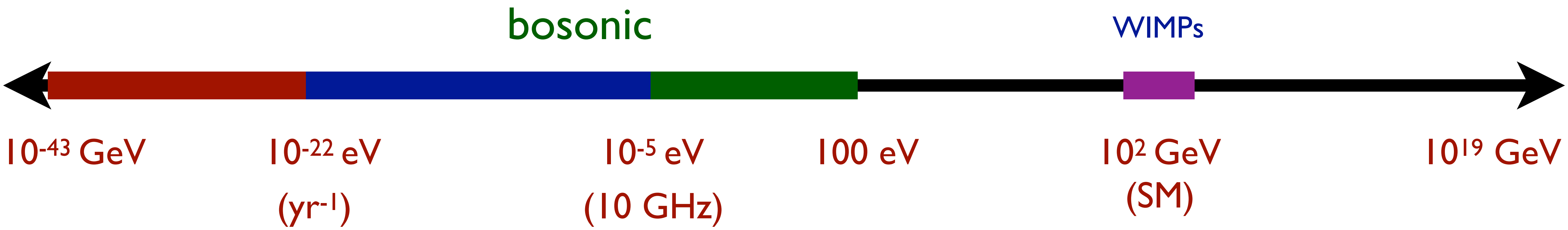

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How do we search for them?
This Talk: Bosons between 10 GHz - 10^{-7} Hz
Range includes popular candidates such as the QCD axion

Bosonic Dark Matter

Photons

$$\vec{E} = E_0 \cos(\omega t - \omega x)$$

Detect Photon by measuring time varying field

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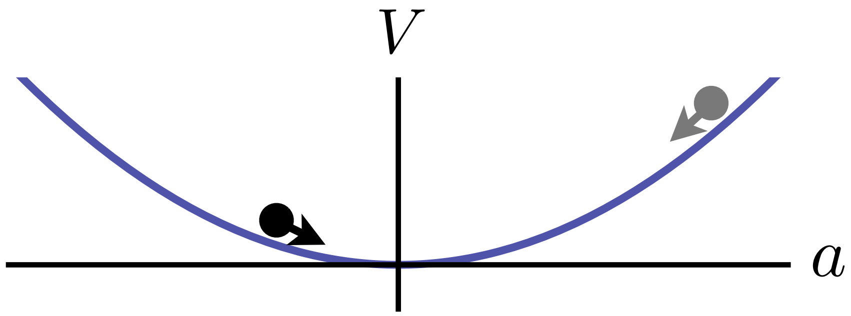
Dark Bosons

Early Universe:
Misalignment Mechanism



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

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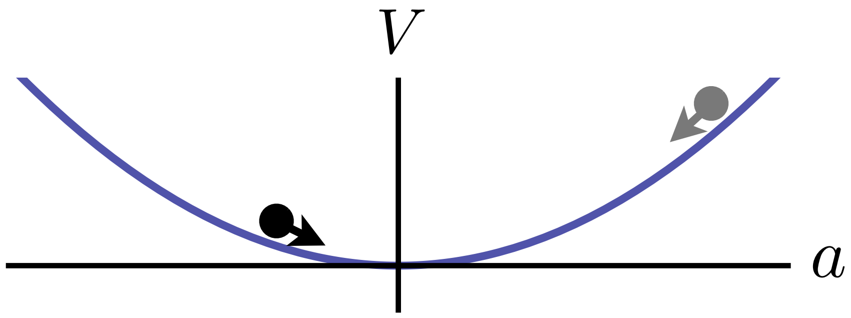

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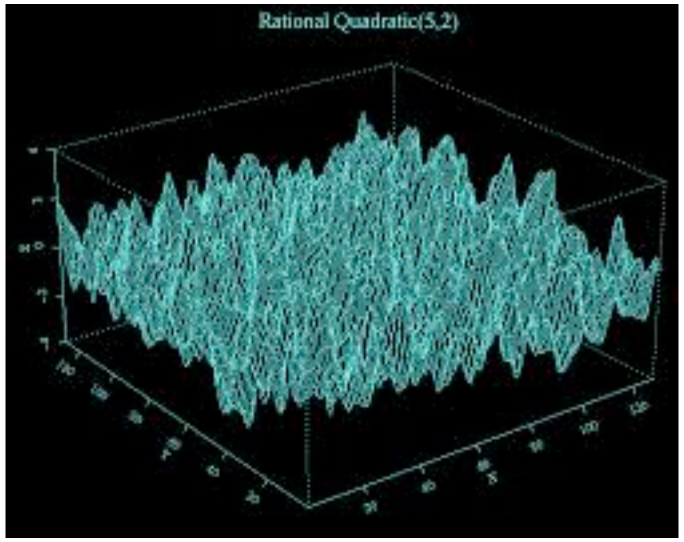
Today: Random Field



Correlation length $\sim 1/(m_a v)$

Coherence Time $\sim 1/(m_a v^2)$ ~ 1 s (MHz/m_a)

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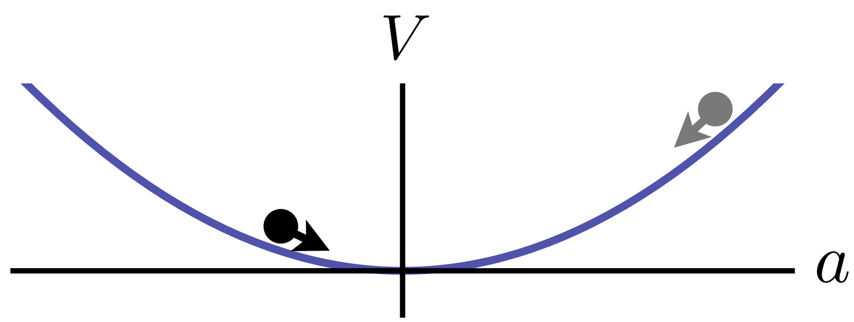

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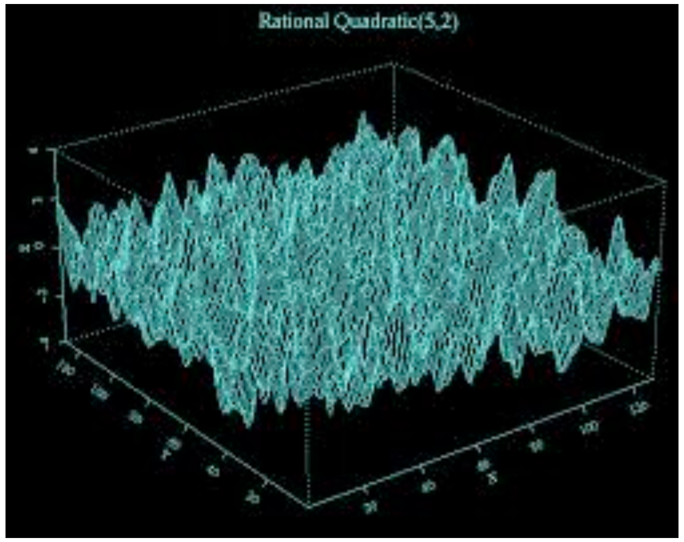

Correlation length $\sim 1/(m_a v)$

Coherence Time $\sim 1/(m_a v^2)$ ~ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

Resonance possible. $Q \sim 10^6$ (set by $v \sim 10^{-3}$)

What kind of Bosons?

Naturalness. Structure set by symmetries.

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Spin 0

Axions or ultra weak coupling

Many UV theories

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Many UV theories

E&M	QCD	Spin	Higgs
$\left(\frac{a}{f_a} F\tilde{F}\right)$	$\left(\frac{a}{f_a} G\tilde{G}\right)$	$\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$	$\left(g\phi H^2\right)$
General Axions	QCD Axion	General Axions	Higgs Portal/ Relaxion

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Many UV theories

- **E&M**: $\left(\frac{a}{f_a} F\tilde{F}\right)$ — General Axions
- **QCD**: $\left(\frac{a}{f_a} G\tilde{G}\right)$ — QCD Axion
- **Spin**: $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$ — General Axions
- **Higgs**: $\left(g\phi H^2\right)$ — Higgs Portal/ Relaxion

Spin 1

Anomaly free

Standard Model couplings

What kind of Bosons?

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- E&M: $\left(\frac{a}{f_a} F\tilde{F}\right)$ — General Axions
- QCD: $\left(\frac{a}{f_a} G\tilde{G}\right)$ — QCD Axion
- Spin: $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$ — General Axions
- Higgs: $\left(g\phi H^2\right)$ — Higgs Portal/ Relaxion

Spin 1

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Standard Model couplings

- Spin: $\left(\frac{F'_{\mu\nu}}{f_a} \bar{N}\sigma^{\mu\nu} N\right)$ — Dipole moment
- E&M: $\left(\epsilon F' F\right)$ — Kinetic Mixing
- Current: $\left(g A'_\mu J^\mu_{B-L}\right)$ — B-L

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E&M	QCD	Spin	Higgs
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Dipole moment	Kinetic Mixing	B-L

$$\text{Dark Matter} \implies a = a_0 \cos\left(m_a t\right)$$

a/c signal between 10^{-7} Hz - 10 GHz

Observable Effects

What can the dark matter wind do?

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What can the dark matter wind do?

What can a classical field do?

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Dark Matter

Oscillating Dark Matter Field (just like oscillating EM field from CMB)

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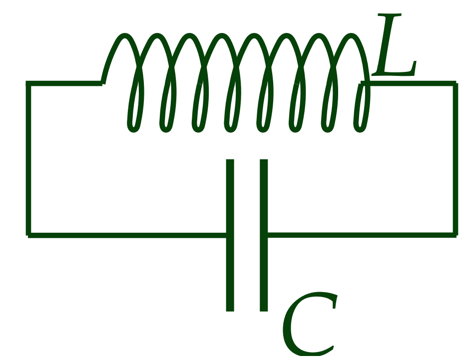

Drive circuit

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Oscillating Dark Matter Field (just like oscillating EM field from CMB)

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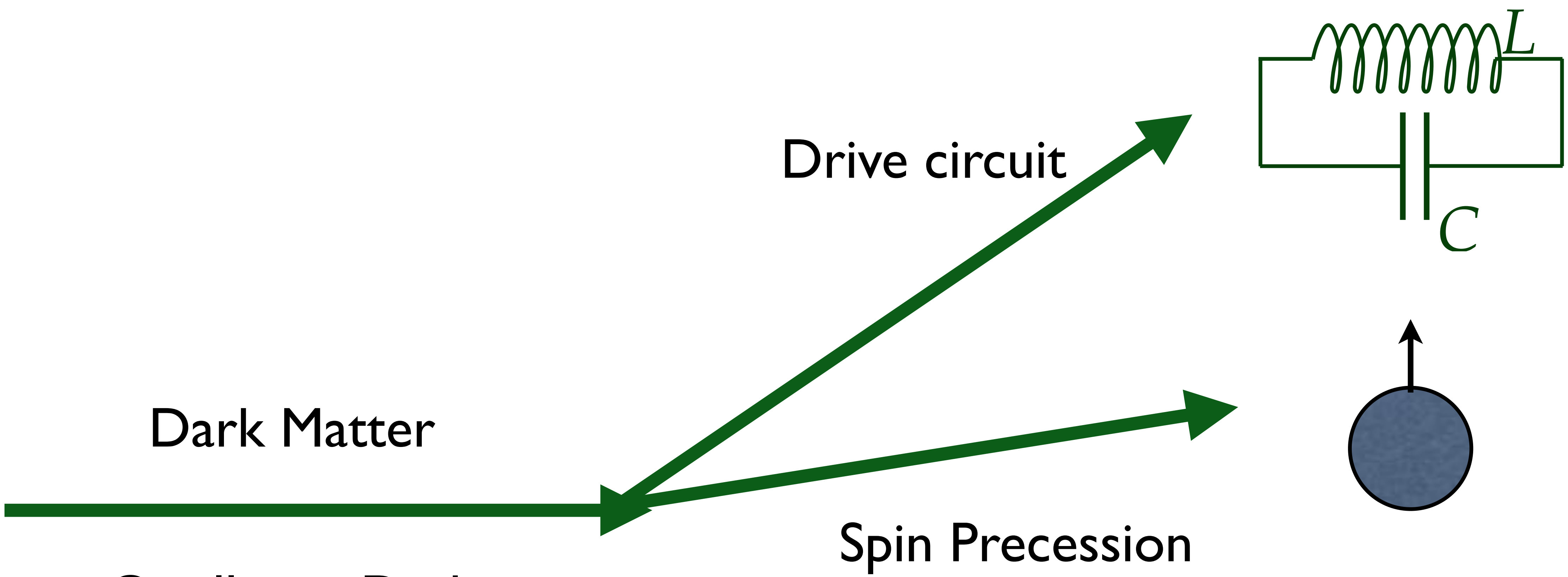

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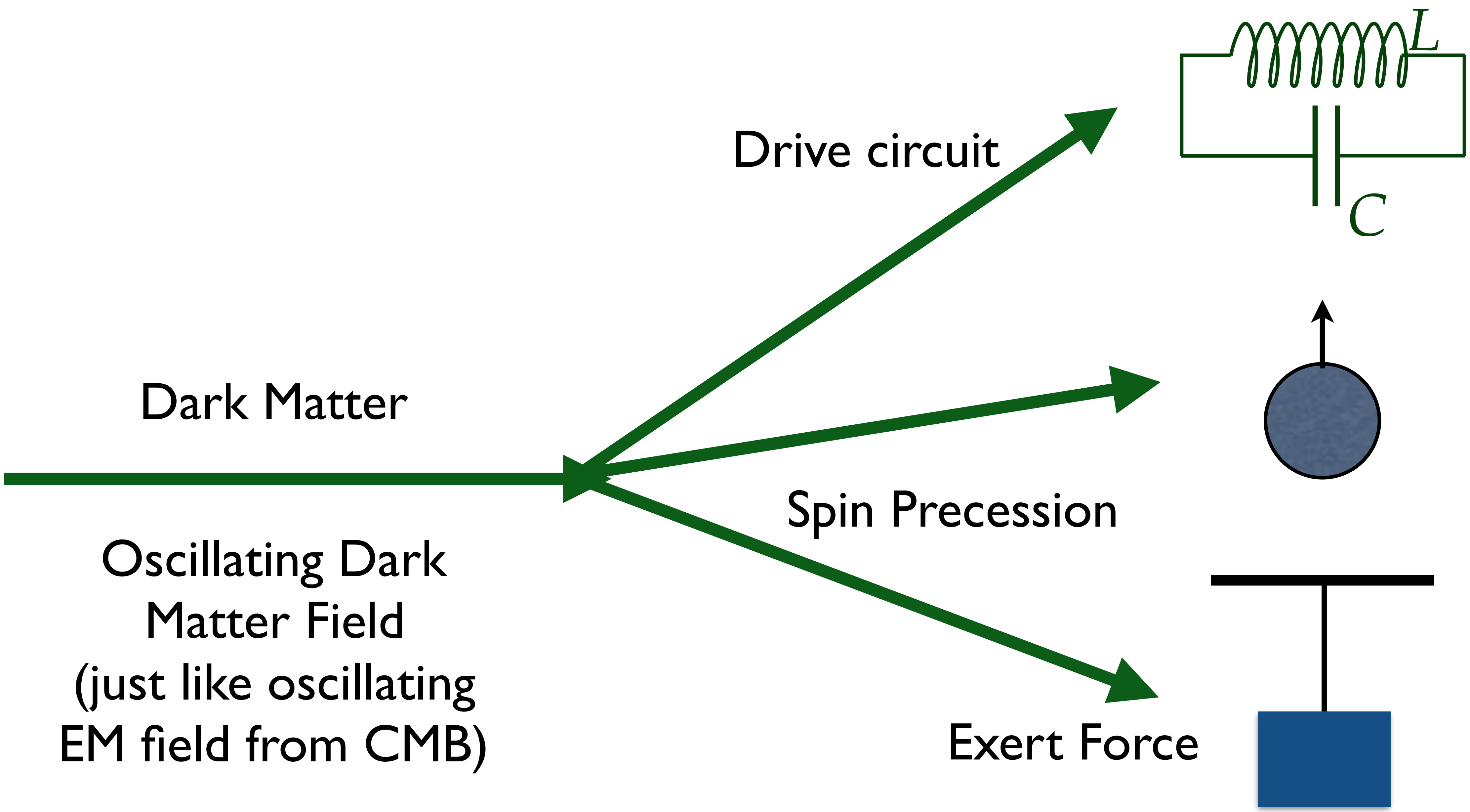

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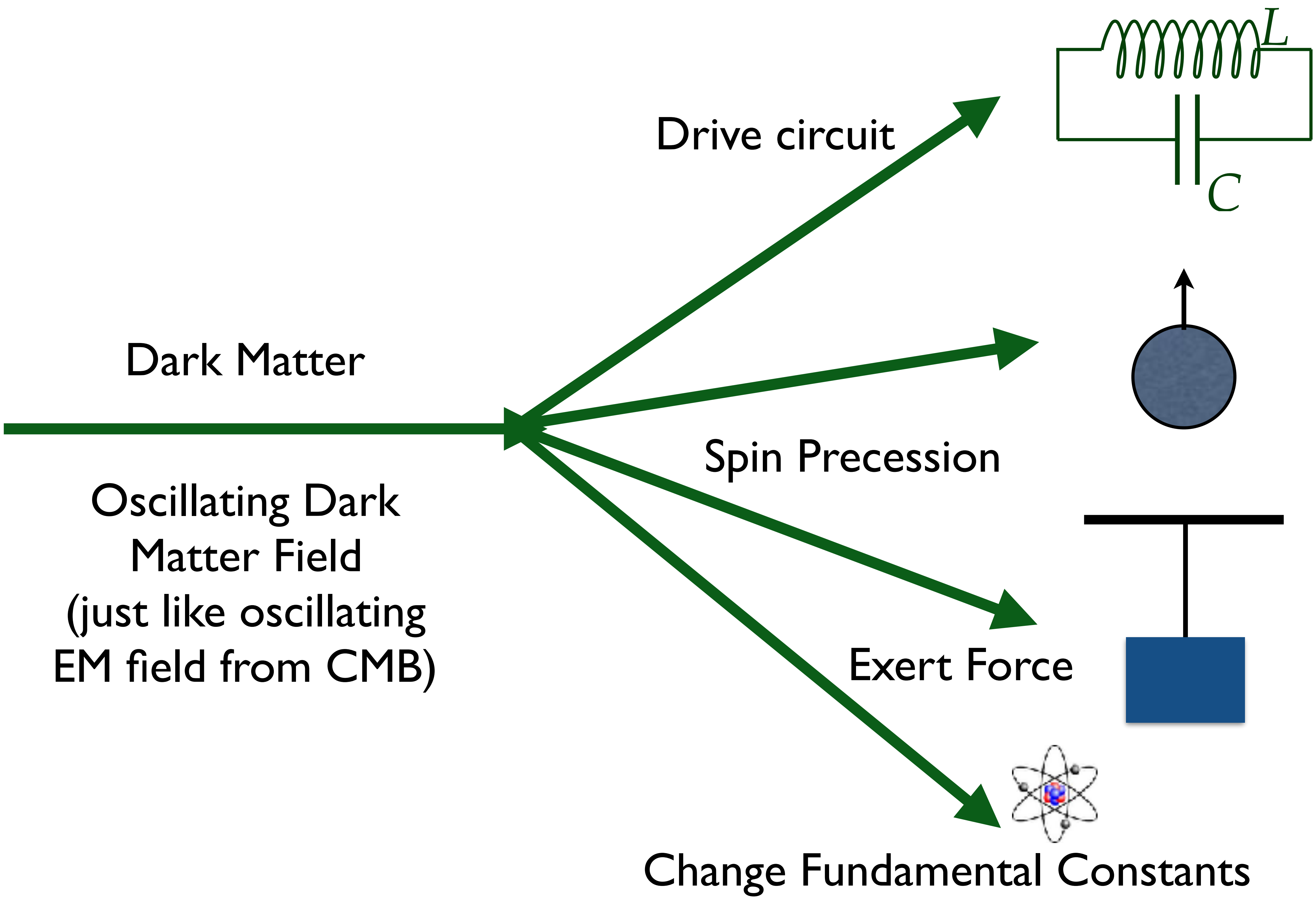

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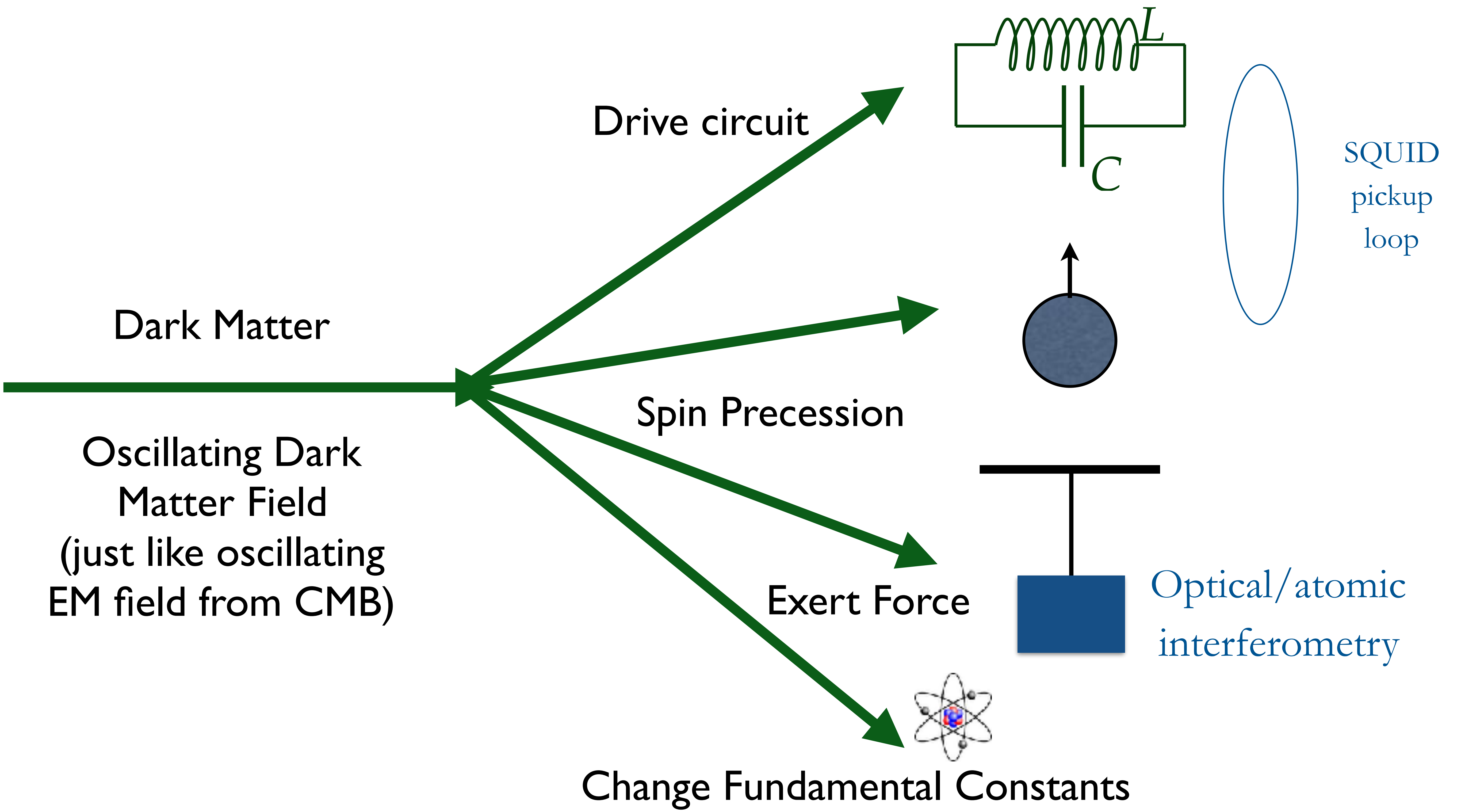

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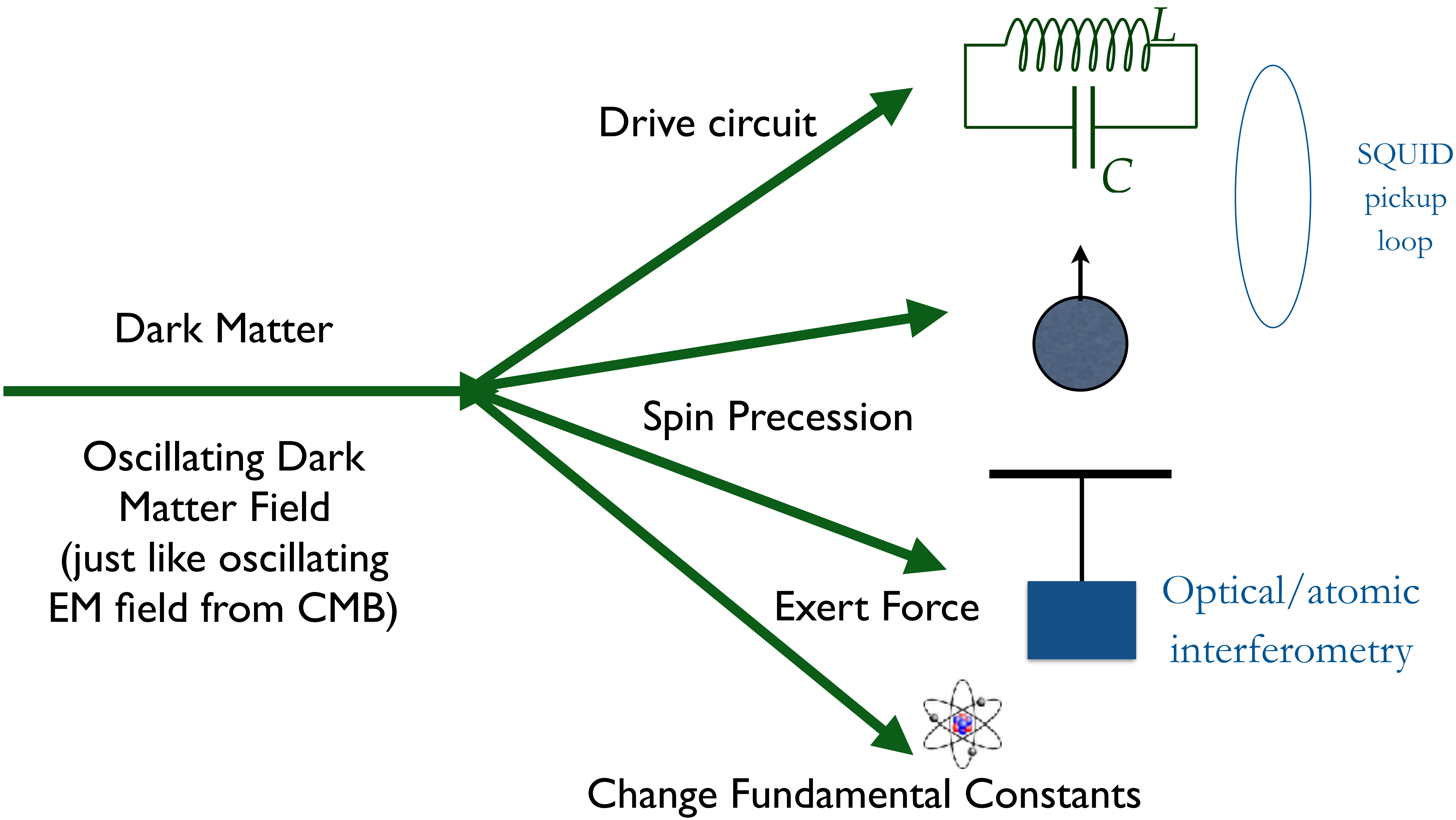

a/c effect, narrow bandwidth around dark matter mass

Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

PRX **4** (2014) arXiv: 1306.6089
PRD **88** (2013) arXiv: 1306.6088
PRD **84** (2011) arXiv: 1101.2691

CASPEr: Axion Effects on Spin

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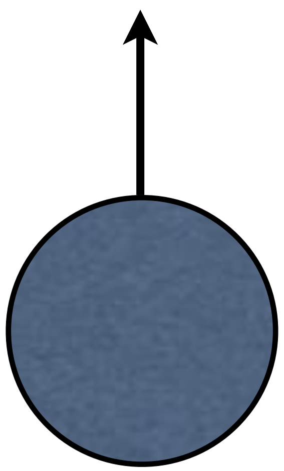
General Axions

Neutron

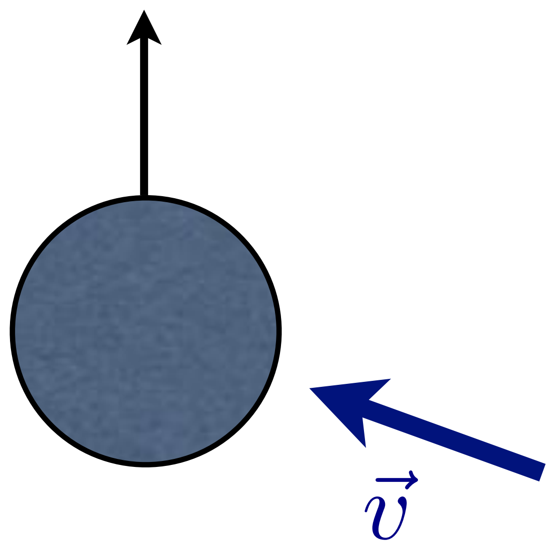


CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind

$$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$$



$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

Spin rotates about dark matter velocity

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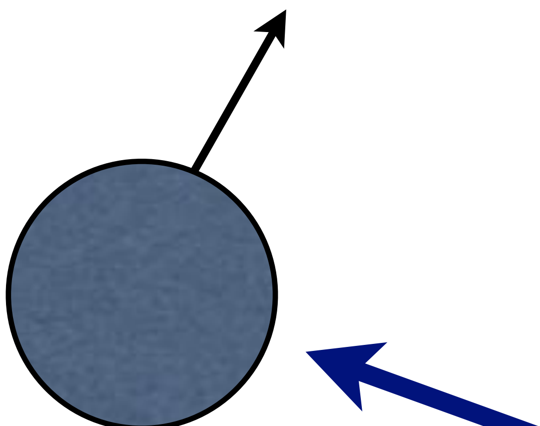

$\vec{v}$

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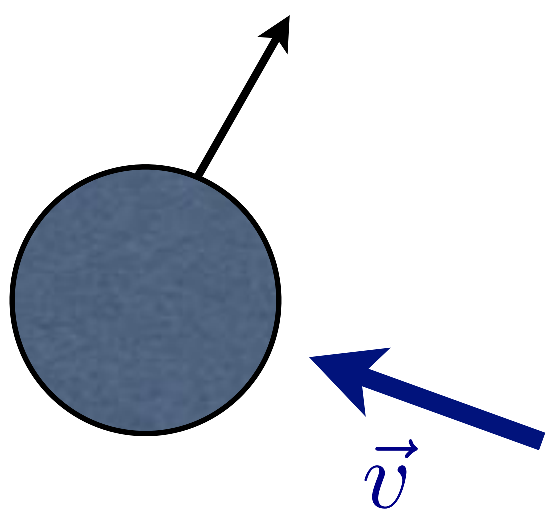

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Effective time varying magnetic field

$$B_{eff} \lesssim 10^{-16}\ \cos\left(m_a t\right)\ \mathrm{T}$$

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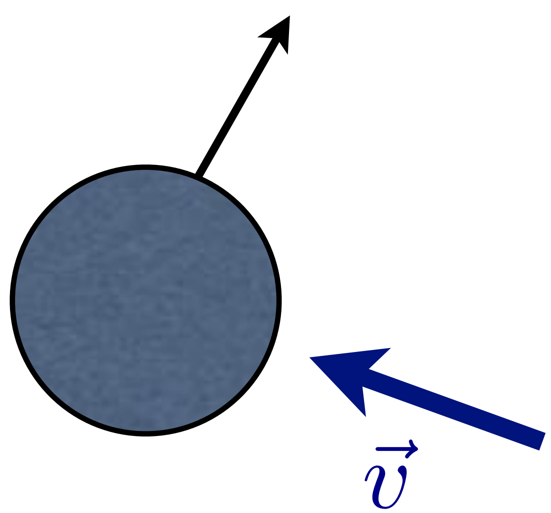

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Other light dark matter (e.g. dark photons) also
induce similar spin precession

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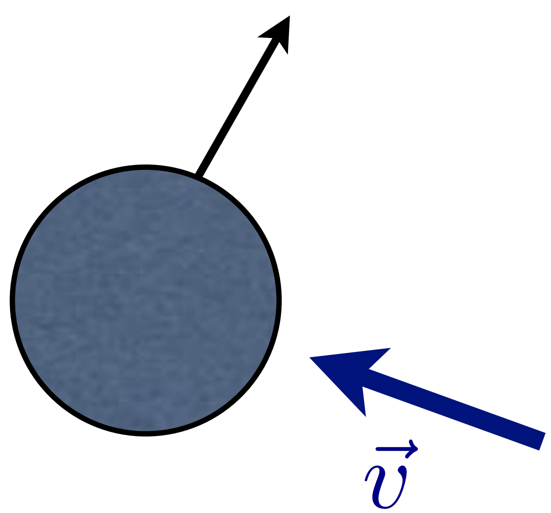

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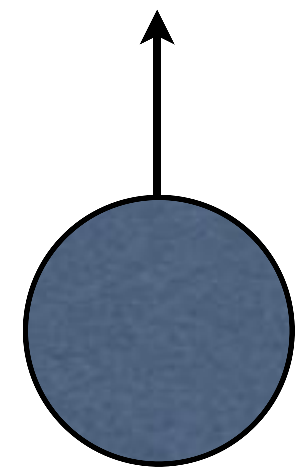

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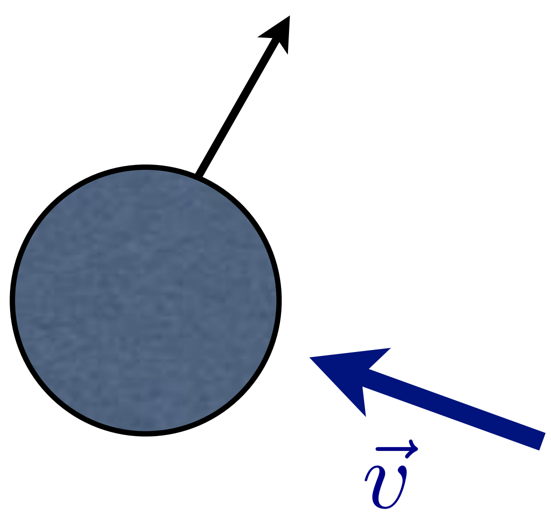

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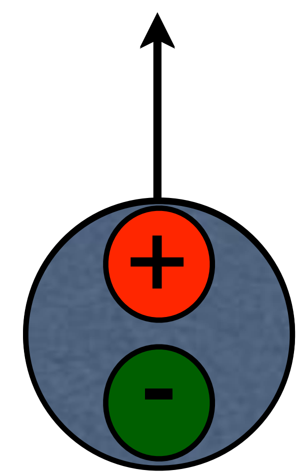
Neutron in QCD Axion Dark Matter



$\left(\frac{a}{f_a}G\tilde{G}\right)$

QCD axion induces electric dipole moment for neutron and proton

Dipole moment along nuclear spin

Oscillating dipole: $d \sim 3\times 10^{-34}\ \cos\left(m_a t\right)\ e\,\mathrm{cm}$

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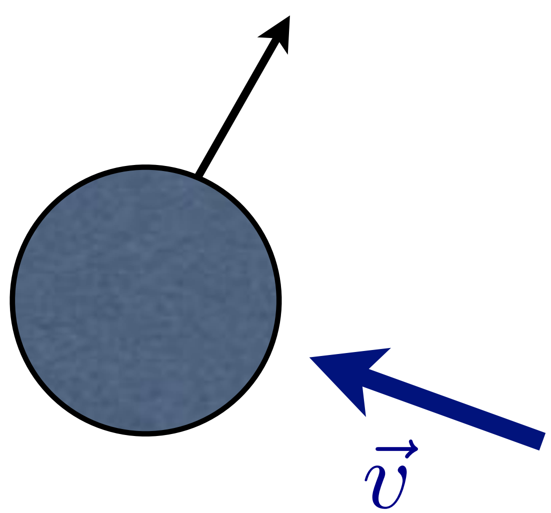

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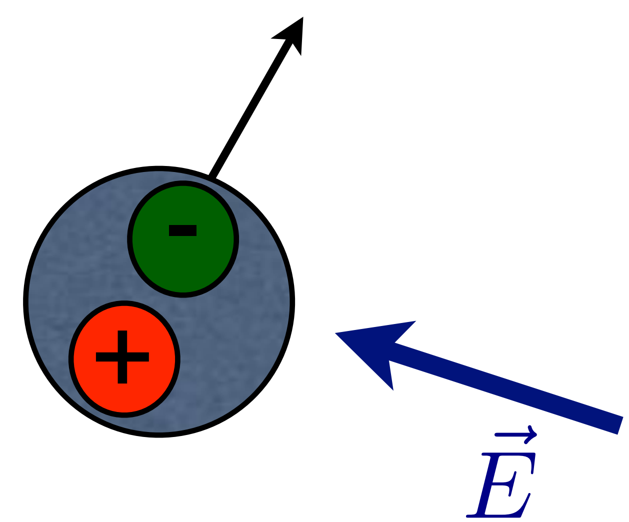

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CASPEr: Axion Effects on Spin

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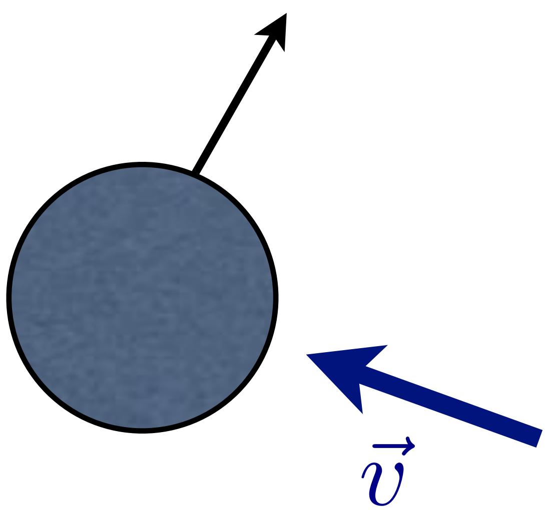

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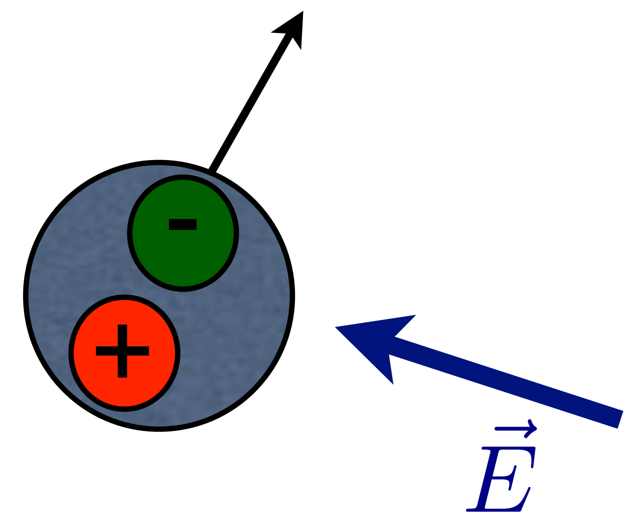

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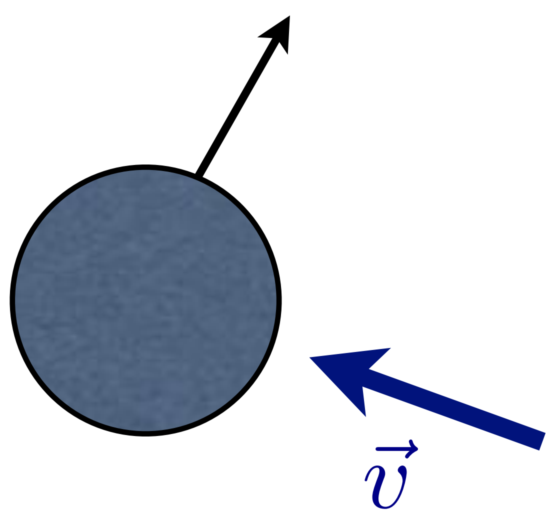

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Measure Spin Rotation, detect Axion

QCD Axion

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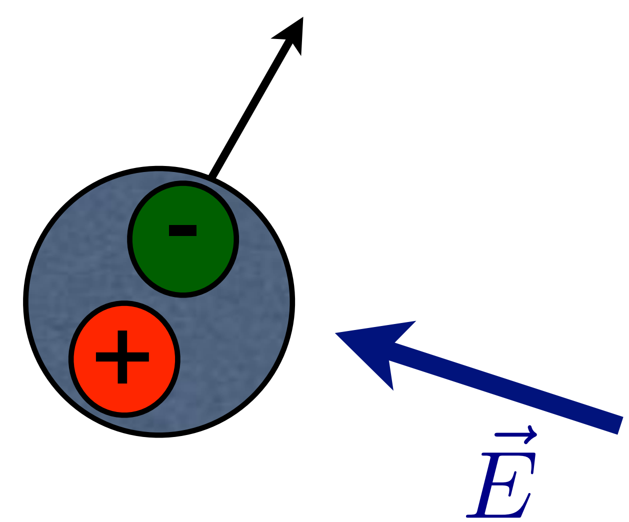

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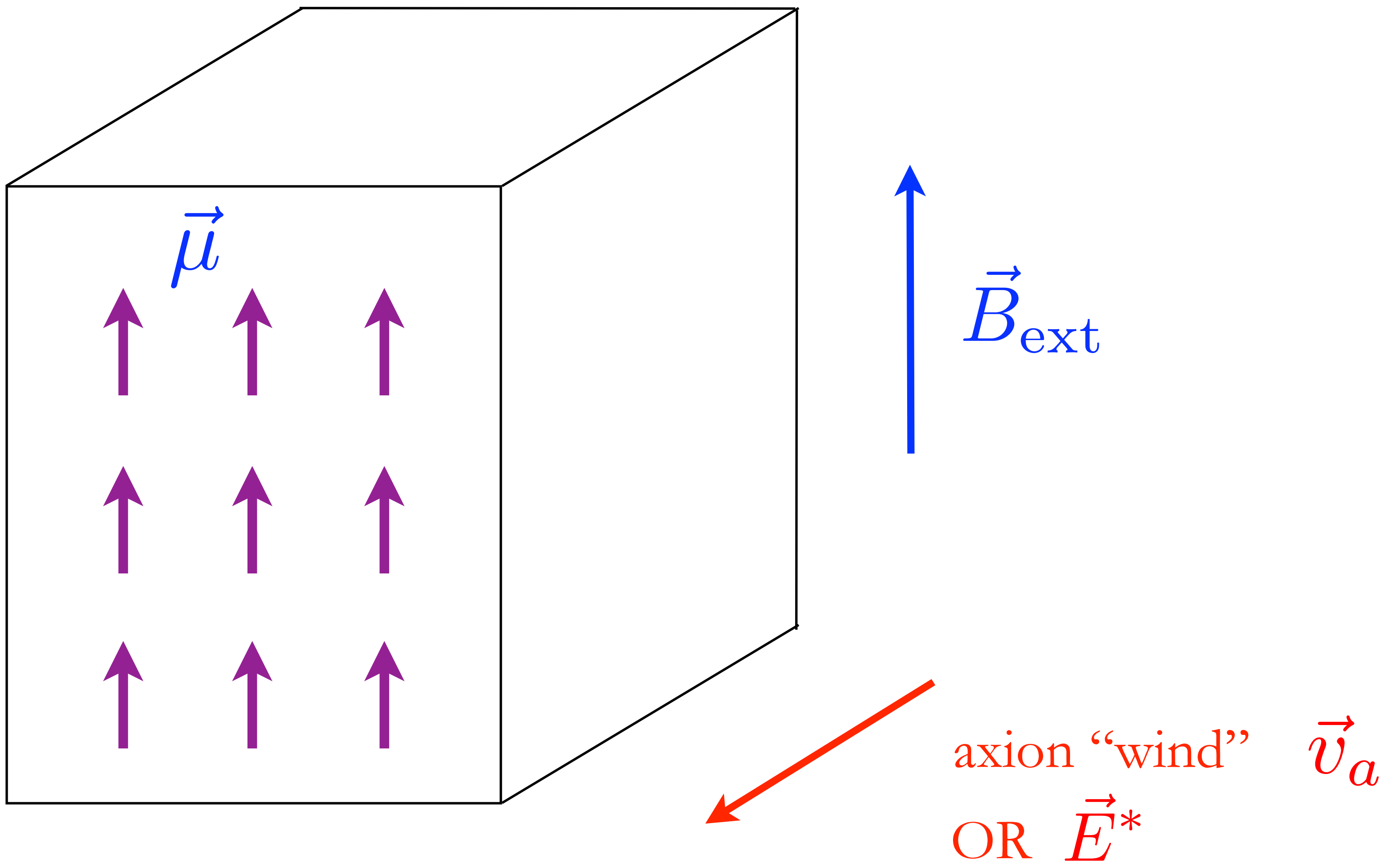
CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

CASPEr

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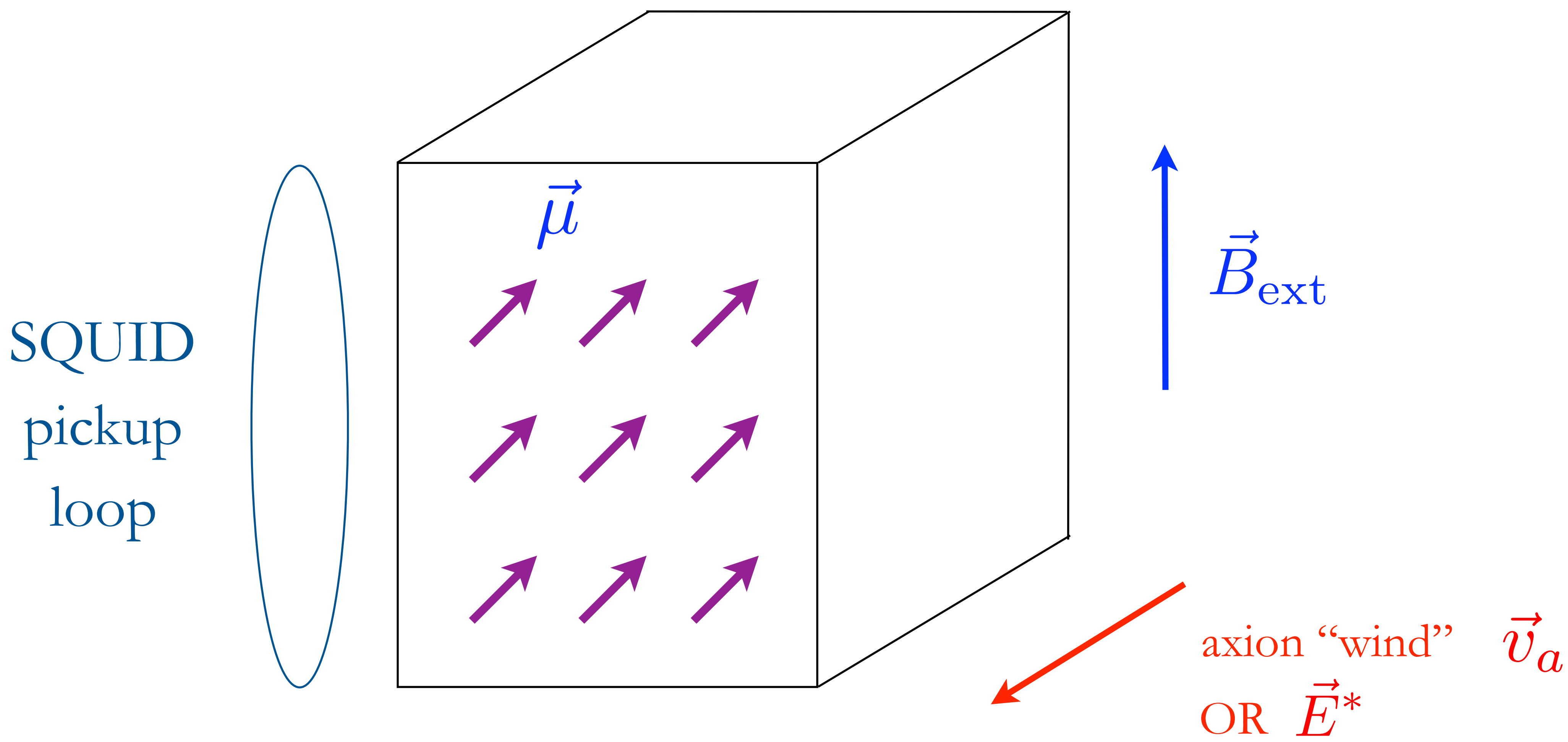


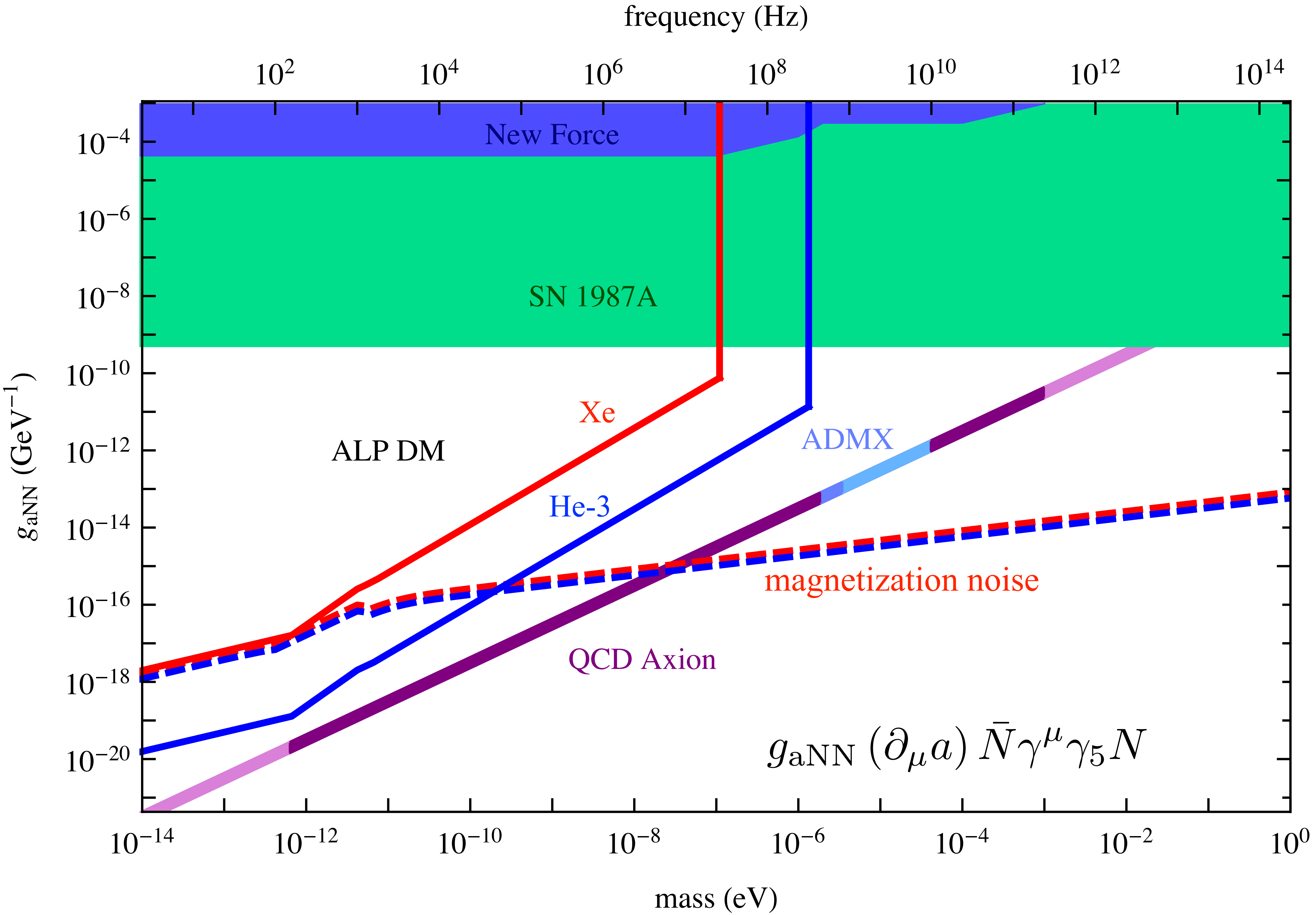
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

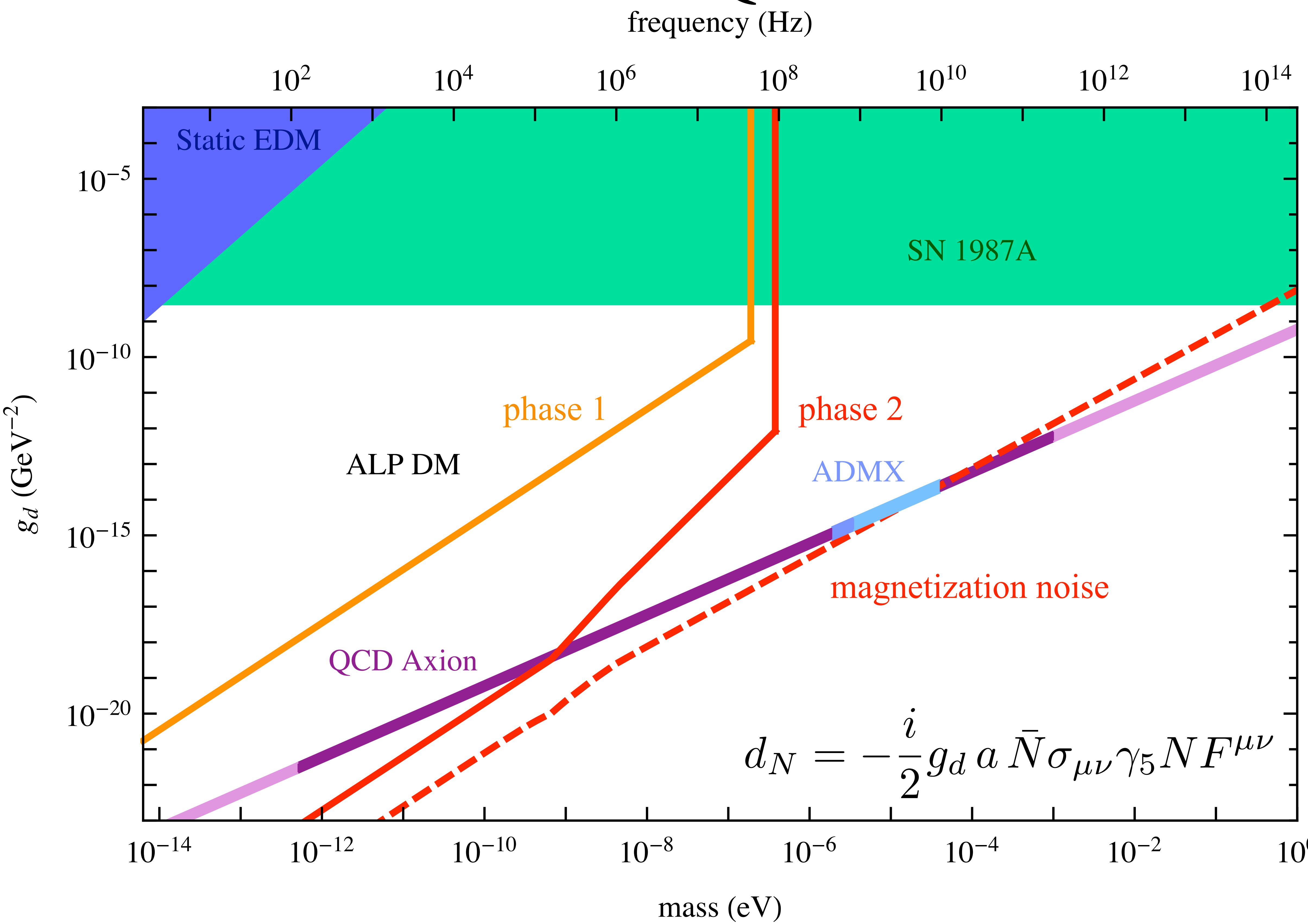
Example materials: LXe, ferroelectric $PbTiO_3$, many others

CASPEr-General Axions



~ year to scan one decade of frequency

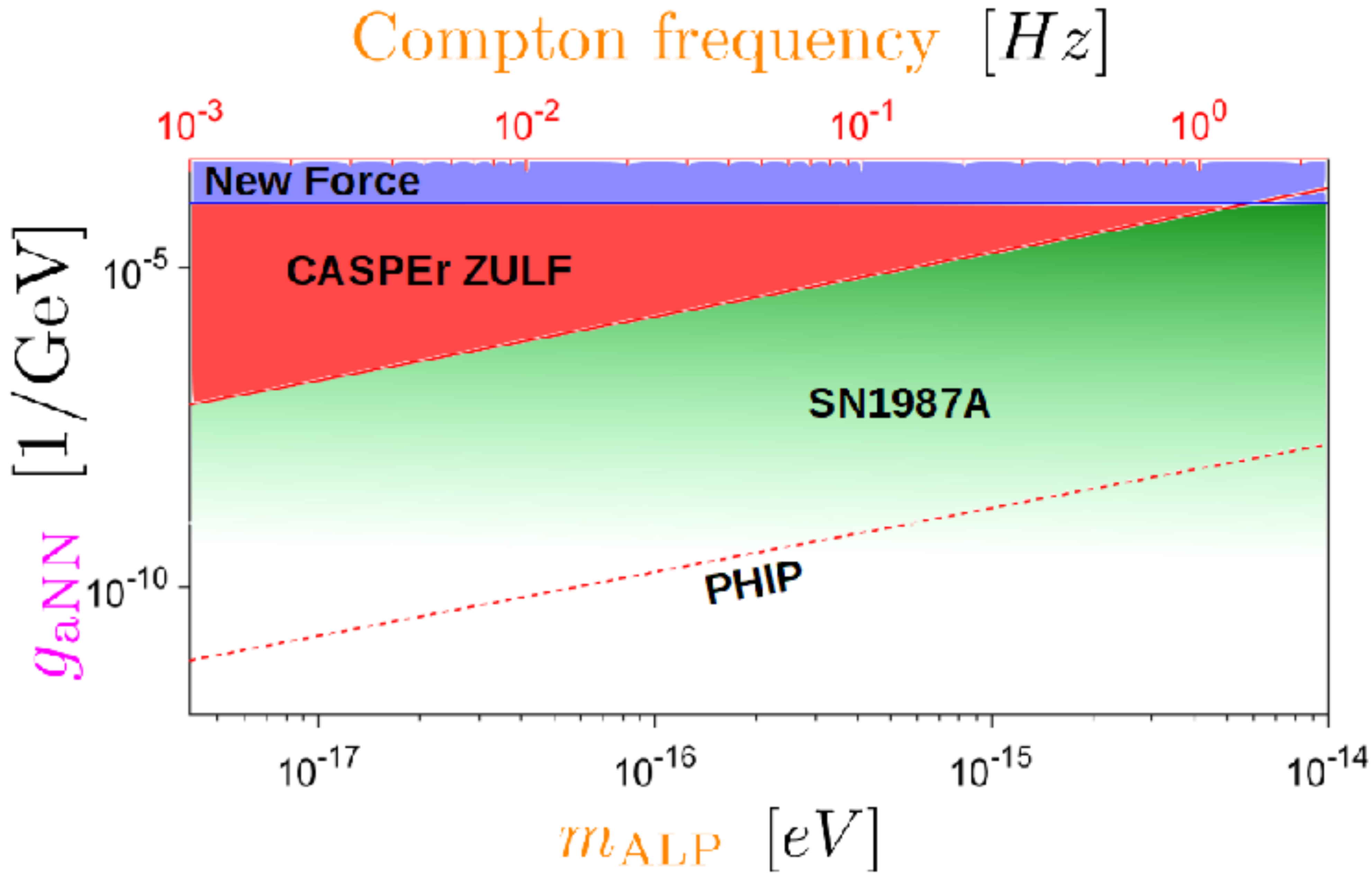
CASPEr-QCD Axion



Verify signal with spatial coherence of axion field

CASPEr-ZULF Results

$$\vec{B}_{\rm ALP} \propto g_{\rm aNN} \cos(m_{\rm ALP} t)\vec{v}$$



10^{-4} nuclear polarization, 24 hr integration time

Dark Matter Detection with Accelerometers

with

Peter Graham
David Kaplan
Jeremy Mardon
William Terrano

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m^2_{\gamma'}A'_{\mu}A'^{\mu} - gJ^{\mu}_{B-L}A'_{\mu}$$

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

Force experiments constrain $g < 10^{-21}$

B-L Dark Matter

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oscillating E' field (dark matter) **can accelerate atoms**

Force depends on net neutron number - violates equivalence principle. Dark matter exerts time dependent equivalence principle violating force!

The Relaxion

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

Hierarchy problem solved through cosmic evolution - does not require any new physics at the LHC

ϕ is a light scalar coupled to higgs with small coupling g

$$\implies \frac{g\phi}{v} m_q \bar{q} q$$

$$\text{Dark matter } \phi \implies \phi = \phi_0 \cos\left(m_\phi \left(t - \vec{\mathrm{v}}.\vec{x}\right)\right)$$

Time variation of masses of fundamental particles

$$\implies \text{force on atoms } \frac{g\nabla\phi}{v} m_q \sim \frac{g m_\phi \vec{\mathrm{v}}}{v} m_q$$

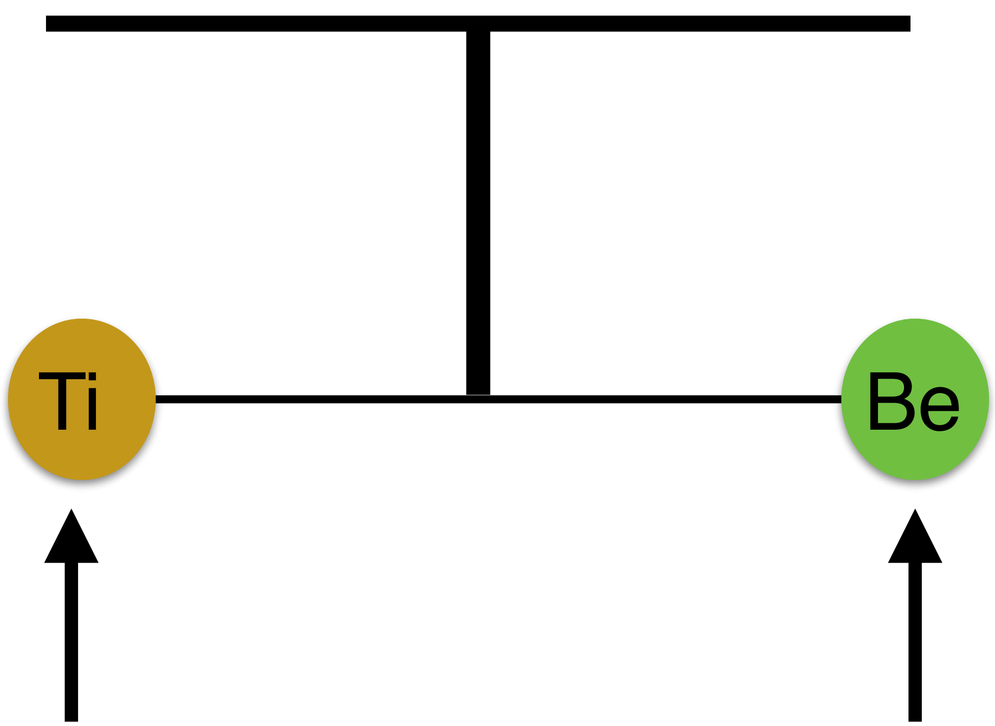
Force violates equivalence principle. Time dependent equivalence principle violation!

Detection Options

Measure relative acceleration between different elements/isotopes.

Leverage existing EP violation searches and work done for gravitational wave detection

Torsion Balance

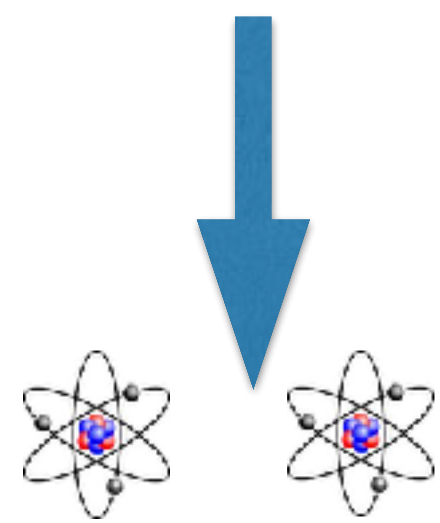


Force from dark matter causes torsion balance to rotate

Measure angle, optical lever arm enhancement

Atom Interferometer

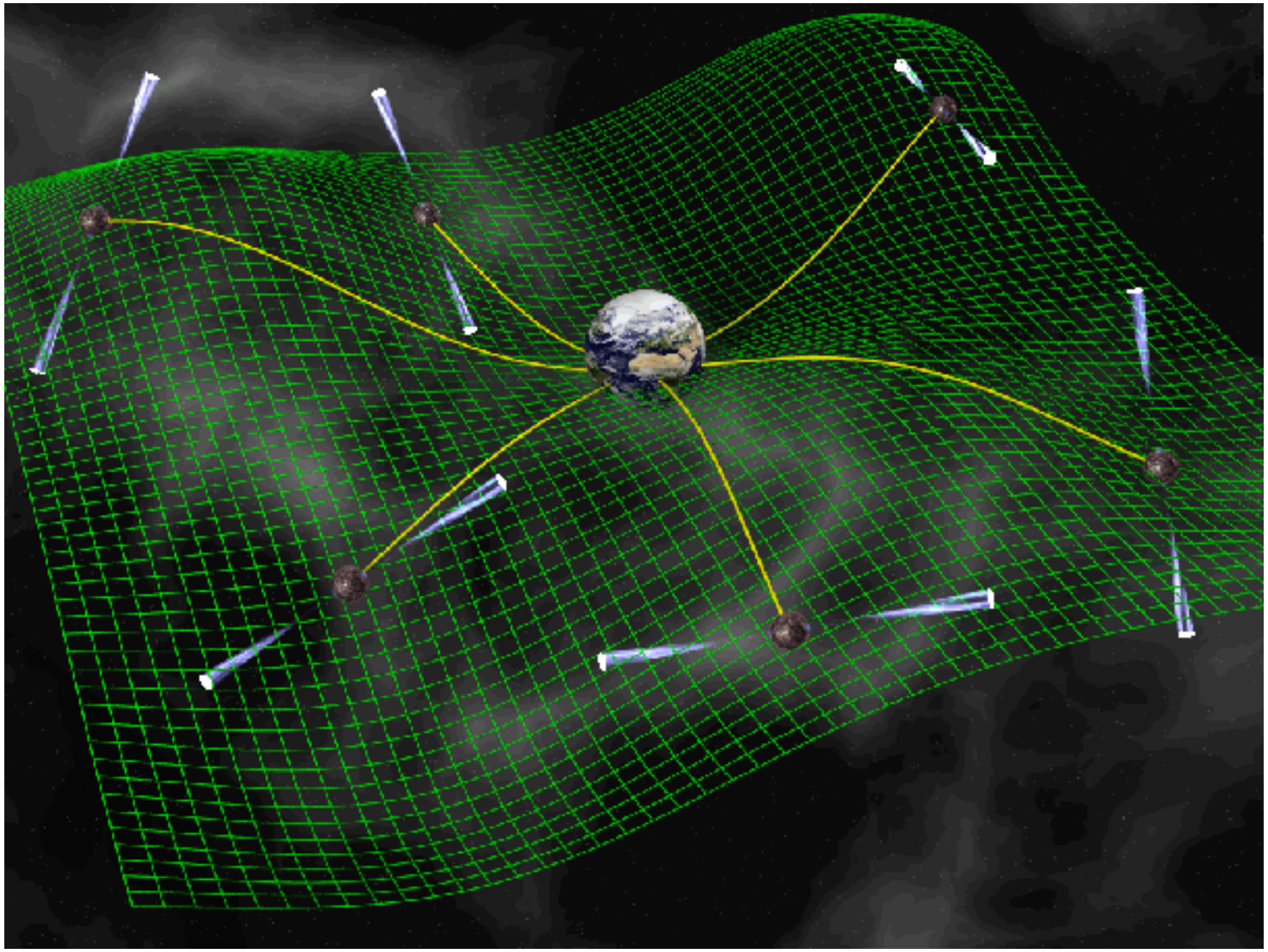
Dark Matter



Differential free fall acceleration

Stanford Facility

Pulsar Timing Arrays

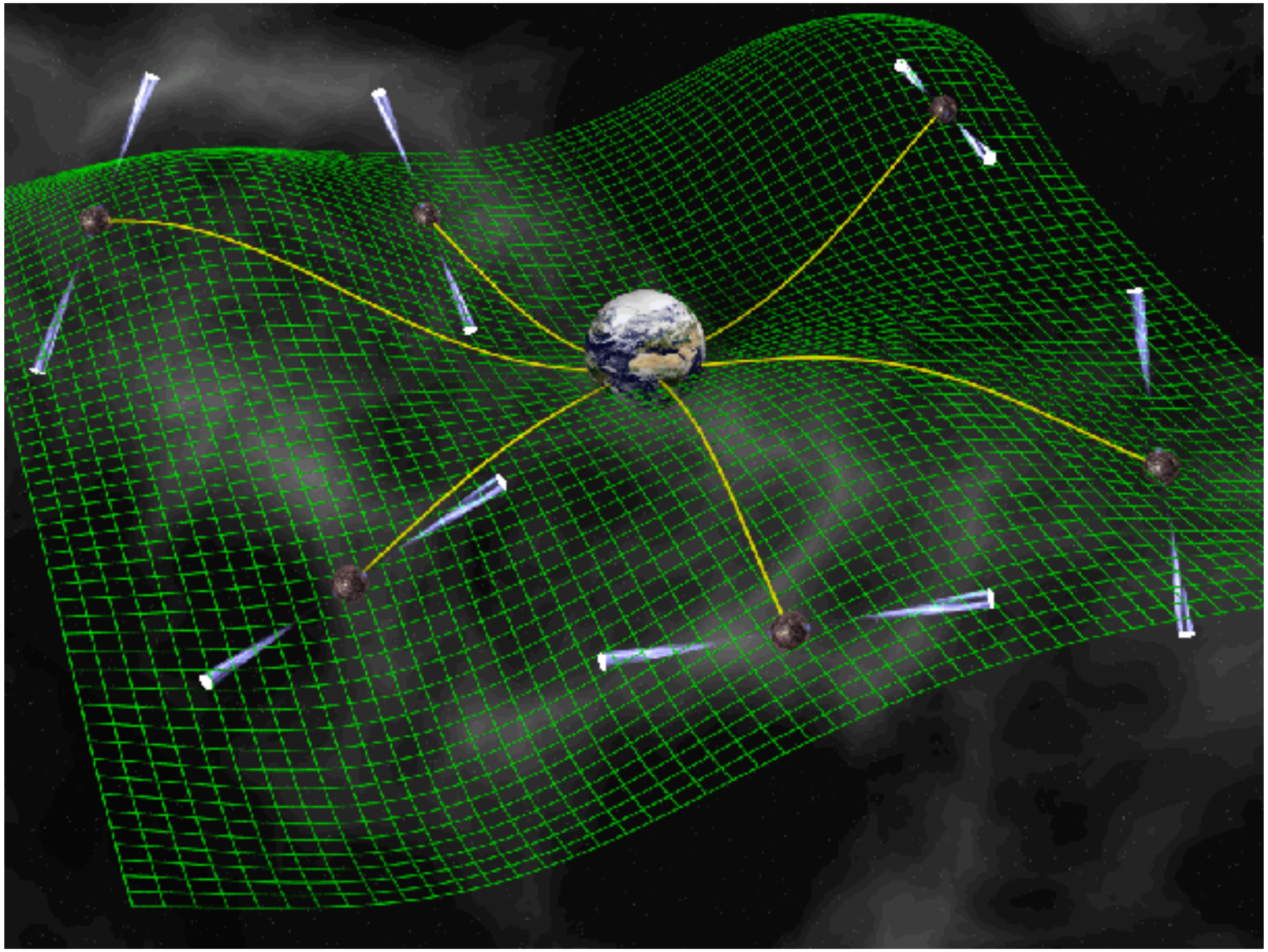


Pulsars are known to have stable rotation - can be used as clocks

Presently used to search for low frequency (100 nHz) gravitational waves.

Pulsar signal modulates due to gravitational wave passing between earth and the pulsar

Pulsar Timing Arrays



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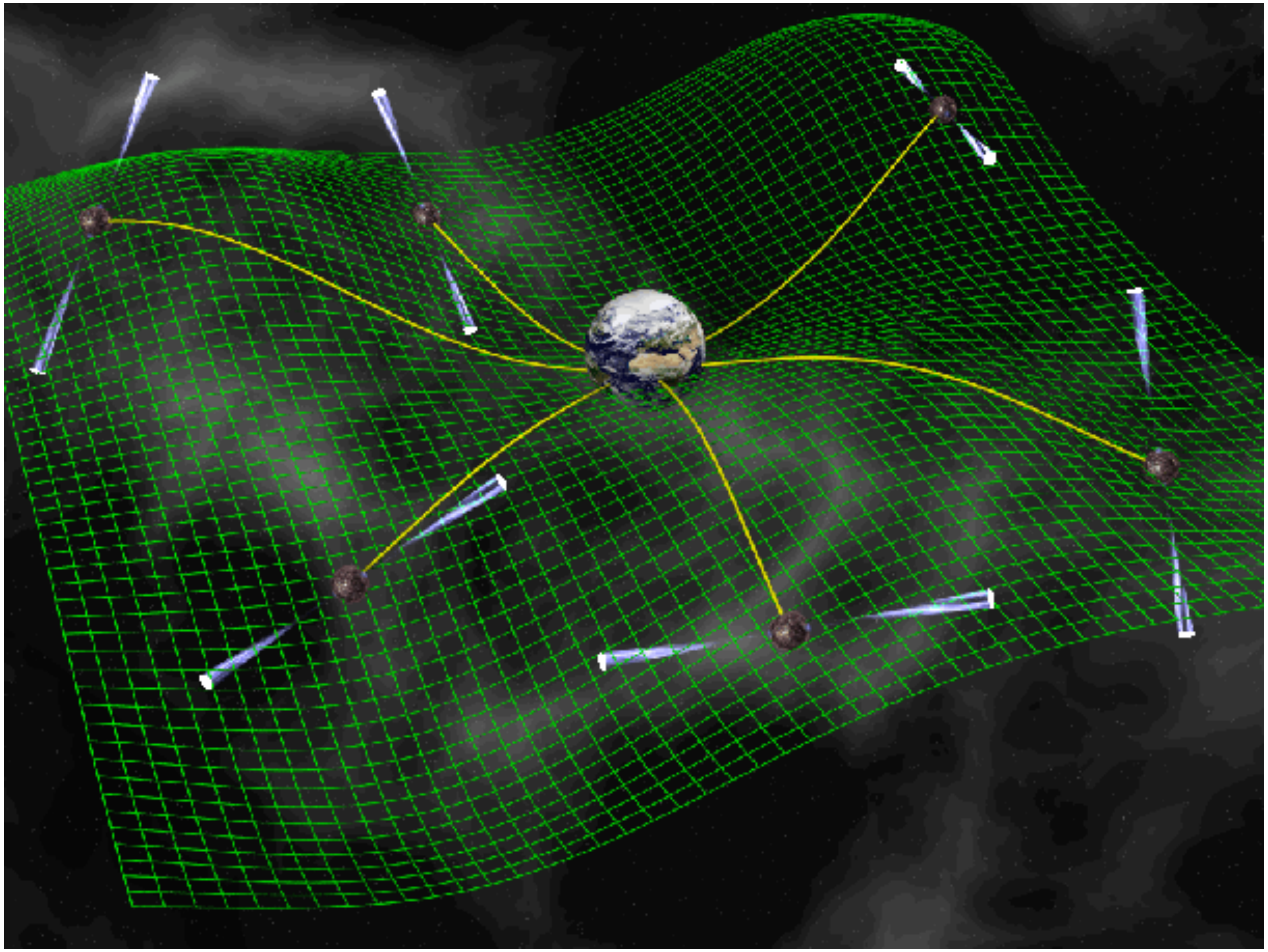

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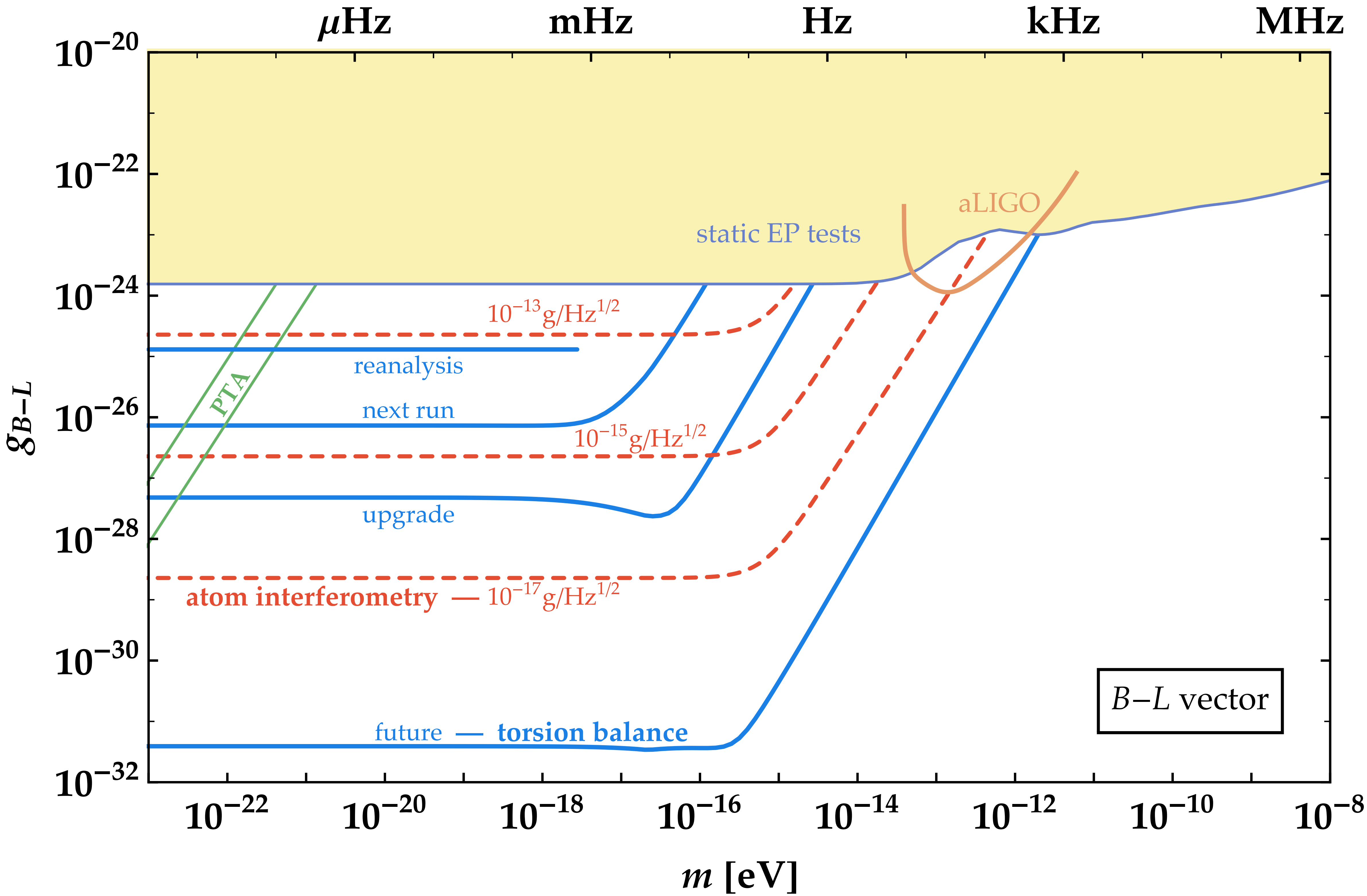
Relaxion changes electron mass at location of Earth - changes clock comparison

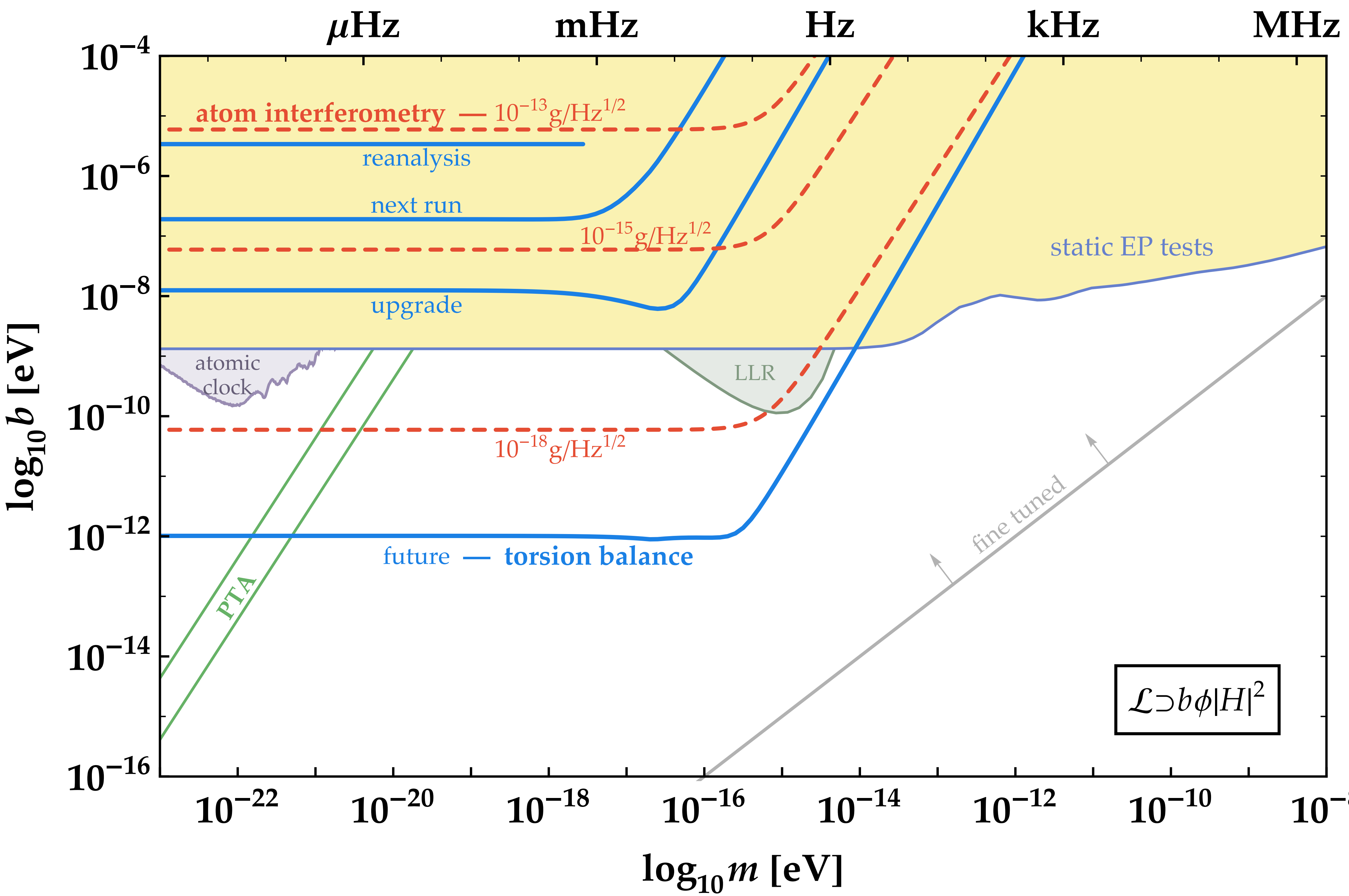
Projected Sensitivities



Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise

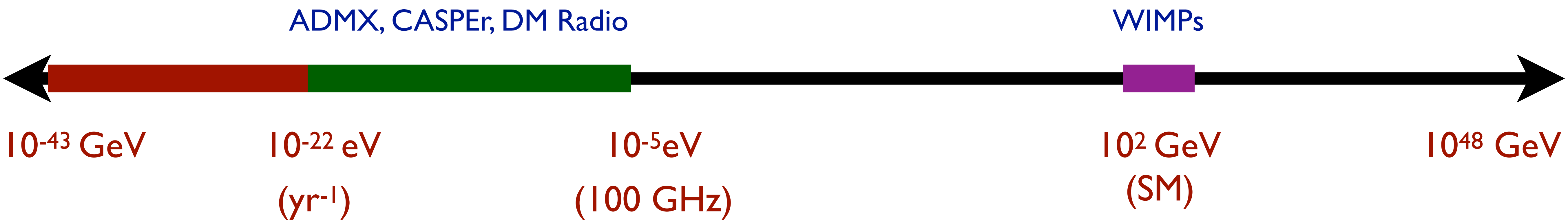
Projected Sensitivities



Torsion Balance limited by fiber thermal noise

Atom interferometers by shot noise

The Dark Matter Landscape



Poor observational constraints on dark matter

Experiments under development can now search for dark matter particles with mass between 10^{-22} eV - 10^{-5} eV, using a variety of precision measurement tools

Need to develop tools to cover full range of possibilities